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Final Report on the Airborne Superconducting Quantum Interference Device (SQUID) Magnetic Gradiometer Program

J. Bradley Nelson

Defence R&D Canada

Technical Memorandum
DREA TM 2001-126
April 2002

Canada

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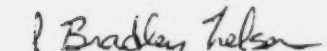

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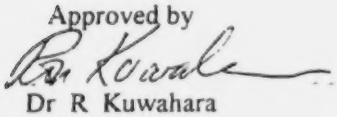

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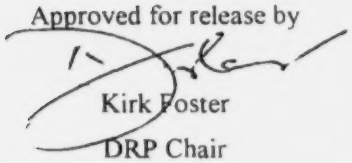

Kirk Foster

DRP Chair

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Abstract

The superconducting quantum interference device (SQUID) program at the Defence Research Establishment Pacific began in the mid-1970's and continued until 1995. At that time the program was shifted to the Defence Research Establishment Atlantic where it continued until July 2000. The goal of this program was to develop and demonstrate a next-generation airborne magnetic gradient sensor for use in anti-submarine warfare Almost all of the sensor development and a large portion of developing the data acquisition software was done under contract, but most of the research on characterizing noise sources in moving gradiometers, and designing/building the electronics and tow-body were done in-house. In June 1998, a flight test of the entire system was conducted using a Canadian Coast Guard helicopter. Although the results looked promising, the program was eventually terminated due to a lack of personnel and resources.

This report gives a brief history of the airborne SQUID program, the results achieved, and the unresolved issues at the time of termination. It also presents the status of other mobile SQUID sensor programs in the US, Germany, the UK, and Australia as of August 2001 for comparison.

Résumé

Le programme de SQUID (détecteur d'énergie quantique à supraconducteurs) a été entrepris au milieu des années 1970 au Centre de recherches pour la défense, Pacifique (CRDP) et s'y est poursuivi jusqu'en 1995 À cette date, il a été transféré au Centre de recherches pour la défense, Atlantique (CRDA), qui l'a mené jusqu'en juillet 2000. Ce programme visait le développement et la démonstration de la prochaine génération de capteurs magnétiques à gradient aéroportés destinés à la guerre anti-sous-marine. La quasi-totalité du développement du capteur et une grande partie du développement du logiciel d'acquisition de données ont été réalisés à contrat, mais les recherches sur la caractérisation des sources de bruit dans les gradiomètres mobiles ainsi que la conception et la construction des composants électroniques et du dispositif de remorquage ont été menées à l'interne. En juin 1998, un essai en vol de l'ensemble du système a été effectué au moyen d'un hélicoptère de la Garde côtière canadienne. Malgré ses résultats prometteurs, le programme a finalement été abandonné, faute de ressources et de personnel suffisants.

Le présent rapport présente un bref historique du programme de SQUID aéroporté ainsi que les résultats atteints et les questions qui restaient à régler lorsque le programme a pris fin. Il présente aussi, à titre comparatif, l'état d'avancement d'autres programmes de capteurs SQUID mobiles qui étaient en cours aux É.-U., en Allemagne, au R.-U. et en Australie en août 2001.

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Executive summary

Background: The superconducting quantum interference device (SQUID) program was begun at the Defence Research Establishment Pacific in the mid-1970's to investigate next-generation gradient magnetic sensors for anti-submarine warfare. The concept of operation for this sensor was to tow it beneath a helicopter because not only did this avoid aircraft-generated magnetic noise, but the gradient target-localization algorithm works equally well at high and low speed. The airborne gradiometer system required the development of a SQUID sensor (done under contract), a data acquisition system (done mostly under contract), electronics (in-house), and a tow-body (in-house). By 1998, all components of the system were completed and a flight trial was conducted using a Canadian Coast Guard helicopter. Although the results looked promising, the trial pointed out many deficiencies in the system including susceptibility to RF interference, problems with the data acquisition software, and some sensor failures. The program was terminated in 2000 due to a lack of resources and personnel. This report gives a brief history of the Canadian airborne SQUID program and the status of other mobile SQUID programs in the US, UK, Germany, and Australia.

Significant Results: For a short portion of the 1998 test flight data, the system recorded the lowest noise ever seen in an airborne SQUID gradiometer system. The white noise was within a factor of 2 of the design specification and, by using adaptive signal processing, all manoeuvre-related artifacts could be removed from the noise spectra. Unfortunately the system was very susceptible to RF interference. A contract with CTF solved the data acquisition software and sensor problems, but the RF interference problem was left outstanding at the termination of the program.

Of the other countries involved in airborne SQUID programs, only Germany is pursuing a low-T_C sensor that may rival the noise level achieved with the Canadian system. They have only conducted stationary trials at present although they expect to flight test a single-component system in the fall of 2001. Canada has assisted the German program by supplying a tow-body and has participated in early trials of the system.

The UK and Australia are developing high-T_C systems but, unless a major breakthrough is made, these systems will have much higher noise in the frequency bands of interest for anti-submarine warfare. However, they have been successfully used as receivers for airborne time-domain electromagnetic (ATEM) surveying.

The US program at Coastal Systems Station in Panama City Florida has concentrated on an underwater system for detecting sea mines and unexploded ordinance since the mid

1980's. Although they have demonstrated low-noise components, they have not yet demonstrated a mobile system with lower noise than Canada achieved. Unfortunately, CSS does not have any funding to improve their system at the time of writing.

Nelson, J. Bradley 2001
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Sommaire

Antécédents : Le programme de SQUID (détecteur d'énergie quantique à supraconducteur) a été créé au Centre de recherches pour la défense, Pacifique au milieu des années 1970 afin d'étudier la prochaine génération de capteurs magnétiques destinés à la guerre anti-sous-marine. Suivant le concept d'exploitation, il était prévu de remorquer ce capteur sous un hélicoptère, non seulement parce que cela permettait d'éviter le bruit magnétique provenant de l'avion, mais aussi parce que l'algorithme de repérage d'objectif par gradient fonctionnait aussi bien à grande vitesse qu'à faible vitesse. Le gradiomètre aéroporté nécessitait le développement d'un capteur SQUID (ce qui a été fait à contrat), d'un système d'acquisition (fait en majeure partie à contrat), de composants électroniques (réalisés à l'interne) et d'un dispositif de remorquage (fabriqué à l'interne). En 1998, tous les composants du système étaient prêts et un essai en vol a été effectué au moyen d'un hélicoptère de la Garde côtière canadienne. Malgré les résultats prometteurs, l'essai a révélé de nombreux défauts du système : susceptibilité l'interference rf, problèmes de fonctionnement du logiciel d'acquisition de données, défaillances des capteurs. Le programme a pris fin en 2000, faute de ressources et de personnel suffisants. Le présent rapport présente un bref historique du programme canadien de SQUID aéroporté ainsi que l'état d'avancement d'autres programmes de SQUID mobiles menés aux É.-U., au R.-U., en Allemagne et en Australie.

Résultats importants : Pour une faible partie des données de vol d'essai de 1988, le système a enregistré le bruit le plus faible jamais enregistré par un gradiomètre SQUID aéroporté. Le bruit blanc se situait à moins d'un facteur de 2 par rapport à la spécification de conception, et le traitement adaptatif du signal a permis de supprimer tous les artefacts associés aux manœuvres qui étaient présents dans les spectres de bruit. Malheureusement, le système était très susceptible l'interference rf. Un contrat signé avec CTF a permis de régler les problèmes du capteur et du logiciel d'acquisition de données, mais le problème de l'interference rf n'était toujours pas réglé lorsque le programme a pris fin.

Parmi les autres pays menant des programmes de SQUID aéroportés, seule l'Allemagne fait l'essai d'un capteur à faible Tc susceptible de rivaliser le niveau de bruit ateint avec le système canadien. Jusqu'à présent, l'Allemagne n'a effectué que des essais fixes, mais un essai en vol d'un système à élément unique est prévu pour l'automne 2001. Le Canada a contribué au programme allemand en fournissant un dispositif de remorquage et a participé aux premiers essais du système.

Le R.-U. et l'Australie travaillent au développement de systèmes à haut Tc mais, à moins que d'importants progrès ne soient réalisés, ces systèmes présenteront un niveau de bruit beaucoup plus élevé dans les bandes de fréquences d'intérêt pour la guerre anti-sous-marine. Toutefois, ils ont été utilisés efficacement comme récepteurs pour des levés électromagnétiques en domaine temporel (ATEM) aéroportés.

Depuis le milieu des années 1980, le programme mené par les É.-U. à la Coastal Systems Station (CSS) de Panama, en Floride, porte essentiellement sur un système sous-marin de détection des mines marines et de l'artillerie non éclatés. Bien que la CSS ait fait la démonstration de composants à faible niveau de bruit, elle n'a pas encore fait la démonstration d'un système mobile à niveau de bruit plus faible que le système canadien. Malheureusement, la CSS n'a pas de fonds pour améliorer son système à l'heure actuelle.

Nelson, J. Bradley 2001
Rapport final sur le dispositif supraconducteur aéroporté à interférence quantique (SQUID), Programme de gradiomètre magnétique
DREA TM 2001-126
Centre de recherches pour la défense, Pacifique

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1. Introduction

The superconducting quantum interference device (SQUID) program was begun in the mid-1970's to investigate next-generation magnetic sensors for anti-submarine warfare (ASW). Because SQUID sensors have the potential for extremely low-noise measurements, it was felt that the best way to utilize that sensitivity was in a gradiometer configuration. The baseline of the envisaged gradiometer was ~ 25 cm making the device, in theory, quite small. However, the cryogenic dewar required to cool the device to 4K would make the whole system on the order of a hundred kg, with a volume of ~ 1 cubic metre.

One of the major advantages of a gradient system is that the data can be inverted to yield a vector pointing towards a dipole source (Ref 1). In traditional magnetic anomaly detection (MAD), the forward speed of the aircraft transforms the DC perturbation of the background field caused by the submarine's hull into a transient. This transient lasts for only a few seconds depending on the speed of the aircraft, the aircraft/submarine geometry, and various other factors. By contrast, the SQUID gradiometer, and the inversion algorithm, work very effectively down to DC. Thus the SQUID gradiometer is ideally suited to helicopters either moving forward at high speed or hovering.

Helicopters generate a great deal of magnetic interference with their many ferrous components and conductive surfaces. The existing aircraft magnetic noise removal algorithms would have to be improved dramatically for an in-board sensor to be successful. Thus it was determined that the sensor would be towed on a long cable to get away from the magnetic noise of the helicopter. The system would be battery powered to avoid the magnetic fields due to electrical currents flowing from the helicopter to the sensor and a fibre-optic cable would be used to communicate with the data acquisition system in the helicopter. Figure 1 illustrates the concept of operations envisaged for the SQUID gradiometer

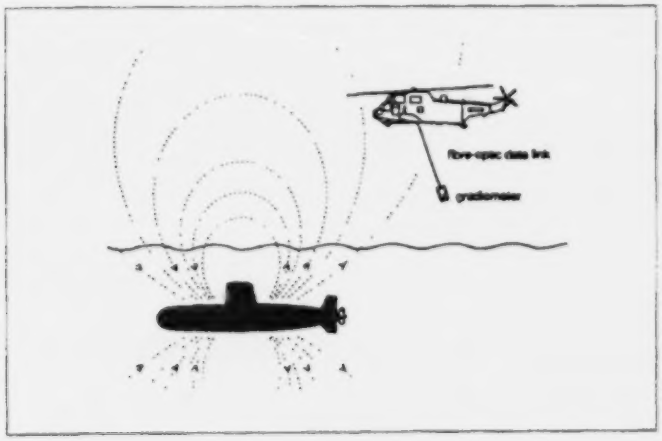

Figure 1 Concept of operations for the airborne SQUID magnetic gradiometer

In the early 1980's field trials showed that the basic sensor worked and the inversion algorithm was robust as long as the sensor was stationary Moving the sensor, however, led to significant increases in the noise - especially in the frequency bands where submarine signals could be expected. From the mid 1980's on, the aim of the program was to understand the source of this enhanced noise, design a new sensor to avoid these sources, and to build and test-fly a low-motion-noise system.

In order to demonstrate a low-noise airborne SQUID magnetic gradiometer system, it was necessary to design, build, and test a number of components. These were:

1) the gradiometer sensor and dewar (contracted to CTF Systems Ltd.)
2) data acquisition software/hardware (contracted to Signum Systems Inc)
3) electronics (mostly in-house)
4) a tow-body (in-house).

By the late 1990's, all the components of the low-motion-noise system had been built and it was test flown in the summer of 1998. The flight trial was partially successful in that at times, the total system noise was within a factor of 2 of the design specification. It was the lowest noise ever recorded in an airborne magnetic sensor Unfortunately there were also problems with RF interference, hardware failures, and software problems that had to be addressed before a follow-on trial could be contemplated.

Due to a lack of resources, the program was officially terminated in 2000 before all of those problems could be addressed. The aim of this report is to put the achievements of the program in perspective, describe the remaining obstacles that were unsolved at the time of termination, and to comment briefly on the status of other mobile SQUID gradiometer programs presently underway outside of Canada. Appendix A contains a comprehensive list of all the documents published as part of the SQUID program. Technical details of the program can be found in these papers. Appendix B contains a list of all the contracts funded by the Defence Research Establishment Pacific (DREP) and the Defence Research Establishment Atlantic (DREA) for the duration of the program.

2. History of the SQUID Program

2.1 Early Gradient Sensor Development

1975-1979

The earliest contracts with CTF Systems were aimed at understanding the theoretical properties of Niobium-based superconducting junctions, doing feasibility studies on their effectiveness as anti-submarine warfare sensors, and gaining expertise in making point-contact SQUIDs. By 1979, a one-component point-contact RF-SQUID sensor and associated Series 200 electronics had been built and tested in the lab. The sensor was mounted in a dewar which contained liquid Helium at 4K to keep the Niobium alloy superconducting.

1980-81

CTF constructed a full "3 field component +6 gradient tensor component gradiometer" using pure Niobium point-contact junction RF-SQUIDs This stationary system, using the same Series 200 electronics, was tested both in the lab and at an external field site where dipole tracking was demonstrated The system was checked for RF immunity, mechanical hysteresis, cable motion, mechanical shock, and calibrated for crosstalk and common-mode. In general, the system showed few problems when operated in this stationary mode. (Ref 2)

1982-1983

Based on the success of the stationary trials in 1981, essentially the same system was mounted on a non-magnetic barge and towed behind a small boat on the Fraser River. The gradiometer was towed past several ships to determine if the dipole tracking algorithm would work when the sensor, instead of the target, was moving. The trial was conducted in fresh water instead of seawater to reduce the magnetic signals generated by the waves.

The trial was successful in that the ship signatures were detected and the inversion algorithm yielded accurate position estimates for the targets, but the most significant result was that the noise level increased dramatically when the sensor was moved (Ref 3). Not only did the white noise increase by 20 dB, but the knee of the "1/f" noise moved out well beyond the frequency band of interest. In fact, the noise level increased by more than 40 dB in the 0-1 Hz region. In addition, a number of peculiar "glitches", or small spikes, occurred in the data stream which could not be accounted for.

2.2 Characterizing the Noise Sources
1983-1988

Analysis of the barge-trial data strongly suggested that a simpler gradiometer system would be required to sort out the problems of enhanced noise in moving gradiometers. CTF was contracted to build a much smaller 3-field component, 1-gradient tensor component RF-SQUID system which would operate with the same Series 200 electronics used in the barge-trial. At the same time, a special low-magnetic-noise facility was constructed at CFAD Rocky Point in order to conduct the necessary tests. The facility, shown in Figure 2, had a non-magnetic rocking fixture to enable dynamic testing and had Helmholtz coils built into the walls to null the Earth's field.

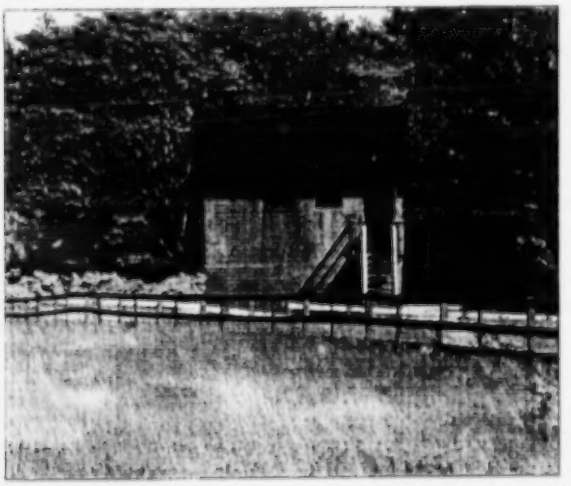

Figure 2. CFAD Rocky Point low-magnetic-noise facility.

By 1988, a number of noise mechanisms had been investigated using the 1-component gradiometer including pressure variations, temperature variations, hysteresis, mechanical vibration, bubbles in the liquid Helium moving past the SQUIDs, trapped flux at cool-down, and a great many problems associated with the Series 200 electronics (Ref 4,5,6). It was felt that most of the noises associated with the SQUID sensors were understood and that the peculiar glitches noted in the barge trial data were caused by the electronics. These electronics were not acceptable for the eventual flight trial because they were not quiet enough, required too much power, and were much too large to fit inside the tow-body. In addition, small temperature fluctuations generated too much noise in the existing RF-SQUIDs so DC-SQUIDs would be required for a useful ASW sensor.

2.3 High-Temperature Superconductor Research 1987-1988

In the late 1980's there was a great deal of effort put into developing high-temperature - or "high-T_C" - superconductors which would go superconducting at 77K instead of at 4K. Such devices could be cooled with liquid Nitrogen instead of liquid Helium which would significantly simplify the operational requirements for an anti-submarine warfare sensor. Consequently DREP contracted with CTF to investigate making thin-film SQUID devices from the first generation high-T_C compound Yttrium-Barium-Copper-Oxide (YBCO).

The conclusion of the final report from this contract was that although the techniques for manufacturing thin-film high-T_C devices had been developed, the "1/f" noise of the devices seriously degraded their performance at the frequencies of interest for anti-submarine warfare. (Ref 7) This noise was thought to be caused by thermally driven flux motion in both the thin-films and the Josephson Junctions. The operating point (77K) was too close to the superconducting transition temperature so small temperature fluctuations had a severe effect. All other groups working on YBCO-based devices reported similar noise levels, but early work on Thallium-Barium-Calcium-Copper-Oxide superconductors looked promising (Ref 8) These materials have transition temperatures in the range of 100-120K and thus offered the promise of less flux-pinning noise.

1989-1991

In early 1989, a contract was let to CTF to develop the fabrication and patterning processes required to make Thallium-based thin-film devices, and to fabricate and measure the properties of DC-SQUIDs made from the material. Since Thallium is a highly toxic material, a number of modifications to the CTF facility were required. Although CTF developed a great deal of expertise in the handling and fabrication techniques required to make thin-film devices, poor quality DC-SQUIDs were produced. (Ref 9) This was attributed to the extreme difficulty in making pure-phase thin film devices and a severe flux pinning problem in the multi-phase devices. Although several recommendations for improving the quality of the material were proposed by CTF, DREP felt that the noise problems could not be overcome in the foreseeable future with the limited funding available.

2.4 The Final Gradiometer and Dewar 1991-1992

By 1991 it was apparent that the airborne gradiometer would have to use low-T_C (Niobium) thin-film sensors. CTF was awarded a contract to design a 3-field component + 5 gradient tensor component SQUID sensor and associated dewar that would exhibit low-motion-noise while in-

flight. Many of the specifications for the device were based on the extensive testing conducted at CFAD Rocky Point in the mid-to-late 1980's By mid 1992, CTF had produced a design which was expected to achieve noise levels of ~ 10^{-5} nT/m/√Hz in the gradient channels (Ref 10).

1994-1998

Although the design for the final 3-field component + 5 gradient tensor component SQUID sensor and associated dewar been produced by mid-1992, the contract to build the device was only signed in December 1993 and work began in early 1994 Originally envisaged as a 3-year project, budget cutbacks and the transitioning of DREP to EDRD in 1995 stretched the project out to mid-1998 Table 1 lists the design specifications for the gradiometer

Table 1 Design specifications for the "3-field component + 5 gradient tensor component" DC-SQUID gradiometer

Parameter	Specification
Outside height	<1 60 m
Outside diameter	<0 44 m
Liquid-Helium consumption	<5 litres/day
Dewar material outer wall	fibreglass
Dewar material inner wall	quartz-fibre composite
RF shield	aluminized mylar
Superinsulation	aluminized mylar, > 0 025 m from pickup coils
Getter	~ 0 5 kg of getter material, > 0 7 m from pickup coils
Insert material	fused quartz
Bubble Shield	bubbles > 0 015 m from substrate
Noise of magnetometer channels	<3000 fT/√Hz
Noise on gradiometer channels	<30 fT/m/√Hz
Common mode coefficients	$<2 \times 10^{-4}$
Gradient response to acceleration	<250 fT/m for a 1 g acceleration
SQUID flux noise	$<3 \times 10^{-5}$ Φ_o/√Hz @ 0 1 Hz
Input coupling noise	<30 ft/m/√Hz with pickup coils attached
Gains for magnetometer channels	100 ± 30 nT/Φ_o
Gains for gradiometer channels	1 0± 0 3 nT/m/Φ_o
Coupled energy sensitivity	$<4 \times 10^{-31}$ J/Hz @ 0 1 Hz
Temperature dependence	<0 03 Φ_o/K
Tilt sensitivity	$<1 \times 10^{-5}$ Φ_o/degree
Non-linearity & hysteresis for $\Delta B<1000$ Φ_o	(error /$\Delta\Phi$) $<1\ 2 \times 10^{-6}$

The gradiometer and dewar, shown in Figure 3, was ground tested and calibrated at the CTF facilities, and met all design specifications except the Gain on the magnetometer channels. (Ref 11) The actual gains obtained were

Gain B_1 = 156 nT/Φ_o
Gain B_2 = 19 nT/Φ_o
Gain B_3 = 167 nT/Φ_o

A full suite of acceptance tests at the Rocky Point low-noise facility were planned including motion noise and RF interference trials. However, the tests were never completed due to a lack of personnel and resources.

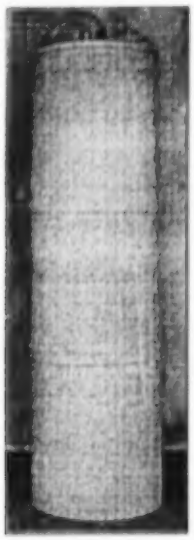

Figure 3. Dewar for the "3-field component + 5 gradient tensor component" DC-SQUID gradiometer. Height = 1.6 m; Diameter =0.40 m.

2.5 Data Acquisition System
1987-1991

At the same time as DREP was contracting with CTF to investigate high-T_C superconducting thin-film technology, several contracts were let to Bridgenorth Signal Processing Inc and Signum Systems to develop the data acquisition software for the as-yet-to-be-built SQUID gradiometer. The system was designed around the TMS320 DSP chip, ran on a 386 portable PC, and recorded the data on a ruggedized Write-Once-Read-Many (WORM) optical drive. At the time, it was felt that this was the only recording system rugged enough to work reliably in the high-vibration environment of a helicopter.

Although in hindsight this had the effect of basing the system on late 1980's hardware technology, it was felt that a PC-based data acquisition system should be built while DREP and CTF determined if the gradiometer would be constructed from a new high-T_C, or the old low-T_C, materials. By 1991, the SQUID controller, communications module, digital-to-analog module, data acquisition and display, self-diagnostics, and SQUID tuning software had been developed. (Ref 12-14)

An important modification was made to the electronics in the mid 1990's to transmit a flag every time there was a reset (a change in the operating point of the SQUID). Each time a reset occurred, a small jump - called the reverse gain error - was introduced into the data. However,

the shape of these jumps was very well known and the amplitude of the jumps on each channel could be measured with a special calibration process. Thus a compensating signal could be generated from the flags, the known shape of the jumps, and the measured amplitudes. This technique allowed the true noise level of the system to be measured

2.6 Electronics
1988-1996

While the data acquisition software was being developed, new low-power, light-weight, non-magnetic electronics were being developed at DREP. Early work with CTF looked at various designs for the analog feedback circuitry. (Ref 15) In the end, the electronics used a digital feedback loop which allowed the system to operate over a very high dynamic range in rapidly changing field and gradient conditions The electronics were powered by gel-cell batteries and would be positioned on top of the dewar to avoid the magnetic interference from running power down from the helicopter. The SQUID outputs were converted to digital optical signals within the electronics and routed to the data acquisition PC by a fibre-optic cable The fibre-optic cable also carried setup, tuning, and diagnostic commands from the data acquisition software to the electronics.

The electronics were extensively tested in the early-1990's using the PC-based data acquisition system and the 1-component gradiometer fitted with a thin-film RF-SQUID sensor. By 1993, the gradiometer was refitted with shielded DC-SQUIDs and the electronics had been modified to work with the new sensors. It was determined that there was a filtering mismatch between the electronics and the new DC-SQUIDs that was generating a significant amount of noise but further modifications to the electronics solved this problem A comprehensive computer simulation of the electronics showed that all the noise mechanisms were understood. (Ref 16) It was concluded that if special attention was paid to the reverse-gain error - that is the slight mismatch of gains when the operating point is intentionally reset - then the total system noise would meet the overall design specification of 3×10^{-5} nT/m/$\sqrt{\text{Hz}}$.

2.7 Tow-Body Development
1992-1993

A vertical-cylinder tow-body was designed and built at DREP to house the gradiometer, electronics, batteries, and dewar The tow-body was instrumented and flown at the Aerospace Engineering Test Establishment (AETE) at CFB Cold Lake to check for towing instabilities. (Ref 17). A pitching instability was discovered and, by adding more mass to the bottom of the tow-body, it was felt that the instability could be overcome A second flight trial of the modified tow-body, also at AETE, proved the concept. (Ref 18)

1996-1997

The final shape of the gradiometer and dewar was slightly different from what was expected in the early 1990's so a second tow-body had to be constructed at DREP. This tow-body was also instrumented and test flown - this time from the Canadian Coast Guard Bell 212 helicopter. A similar pitch instability was discovered near 45 knots (Ref 19) but, again, adding mass to the bottom solved the instability. (Ref 20)

2.8 Helicopter Flight Trial of the System
1998

A flight trial of the entire system - the gradiometer built by CTF, the data acquisition software from Signum Systems, and the electronics and tow-body built by DREP - was conducted using the Canadian Coast Guard Bell 212 helicopter in June 1998. Figure 4 shows the tow-body with the electronics mounted on top of the dewar.

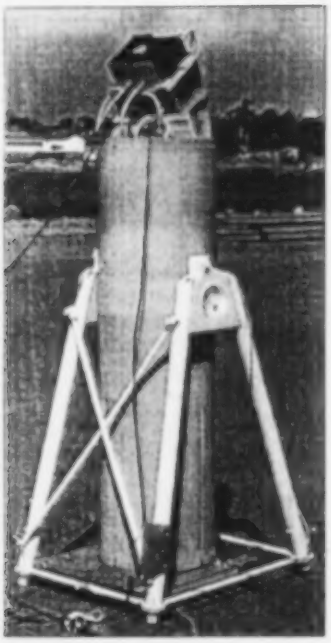

Figure 4. Tow-body with electronics/batteries mounted on top of dewar. Cap for the tow-body is not shown.

The conclusions from this flight trial were (Ref 21):

1) short segments of data had measured white noise levels within a factor of 2 of the design specification (see Figure 5),
2) even with a tow-cable of 65 m, signals from the helicopter were clearly visible (see Figure 5),
3) signal processing further reduced the common-mode by approximately a factor of 1000 (Ref 22),
4) adaptive signal processing removed all manoeuvre-related artifacts from the noise spectra (Ref 22),
3) two SQUIDs needed replacing,
4) the data acquisition system software should be slightly modified to retain the maximum resolution in the recorded data,
5) RF interference was severe during the majority of the flight trial, indicating that better shielding was required.

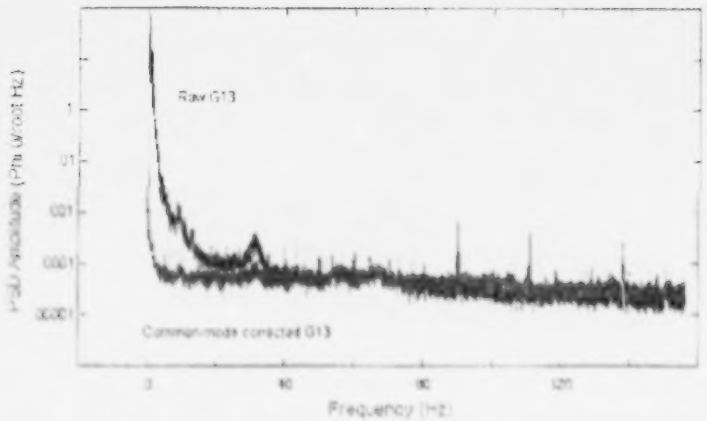

Figure 5. Power Spectral Density of the raw and common-mode-corrected gradient component G_{13} collected during the June 1998 flight trial. The discrete lines are due to the helicopter and the broad lines near 12 and 32 Hz are mechanical resonances. The white noise is ~ 50 fT/m/√Hz.

It should be noted that many other groups who have tried to develop airborne SQUID sensors have also encountered the problem of RF interference (Ref 23-24). Although a great deal of effort was expended in designing and constructing the RF shield, it was clearly insufficient.

2.9 Post-Flight Trial 1999-2000

In 1999 a contract was let to CTF to replace the SQUIDs, modify the data acquisition software and improve the RF shielding. Unfortunately the shielding problem could not be adequately addressed given the small funding available at the time. At the conclusion of this contract, it was determined that the level of resources within DREA was not sufficient to carry on without contracting the work to CTF and CTF felt that it was not in their interests to continue with small contracts. An attempt was made to find partners from the exploration and mining communities, and with foreign defence departments but this was unsuccessful. A decision to terminate the airborne SQUID gradiometer program was made in July 2000.

3. Achievements

The program did make a number of remarkable achievements given the small amount of resources within DREP and DREA devoted to the program. The barge-trial in 1983 clearly demonstrated the excess noise problems with moving gradiometers and changed the focus of the research for many years. The subsequent work at the CFAD Rocky Point low-magnetic-noise facility firmly established the physical mechanisms for that noise and was instrumental in the establishing the final design of the gradiometer. These results were passed on to other researchers in the UK, Germany, and the US, significantly aiding their mobile SQUID programs. The research into high-T_C materials did not ultimately lead to a better airborne gradiometer sensor, but it did develop CTF's expertise in making thin-film devices. CTF has since gone on to become a leading supplier of thin-film SQUID devices for biomedical research. The DREP-built electronics continue to be as quiet as many other SQUID electronics that do not have the restrictions on

weight, volume, or magnetic contamination. CTF is considering developing a very similar fibre-optic-based data acquisition system for their latest biomedical SQUID systems. DREP's tow-body was unusual because it was a vertical cylinder and very little information was available in the literature on the aerodynamics of vertical cylinders. However, the successful design of the tow-body allowed the gradiometer dewar to towed vertically. This greatly simplified the design of the gradiometer for liquid-Helium cooling, boil-off rates, thermal shielding, etc. and thereby reduced the cost of the final system. Finally, when the entire system was test flown, it recorded the lowest noise ever seen in an airborne SQUID gradiometer system. The lessons learned in the Canadian SQUID program have used by UK and German researchers to hasten their programs.

4. Unresolved Problems

What follows is a brief description of the effort required if the program was to be re-opened in the future. The largest unresolved problem with the gradiometer was the RF interference. Preliminary discussions with CTF in 2000 suggested that, because there was very little room inside the tow-body, the best alternative would be to attach a conductive mesh to the outside of the tow-body. The alternative would be to replace the RF shield inside the dewar walls but this might involve re-making the dewar. Also, if the screening is put on the outside of the tow-body, the increased distance from the gradient pickup coils will result in lower Johnson noise from the thermally-generated electrical currents flowing in the conductive mesh.

Solving the RF problem may have allowed DREA to conduct a more successful second flight trial but, since a low-noise segment had already been obtained on the first flight trial, it was unclear what benefit this would provide. In order to conduct a more meaningful experiment, the entire data acquisition system would have to be upgraded. The optical WORM drive is obsolete and even the recording media are not manufactured anymore. Although one might expect it to be a relatively simple matter to record the data on the hard drive, or some removable media such as a 2-Gigabyte JAZ disk, the data acquisition software was written especially for the WORM media. Thus a major re-write of the data acquisition software would be required.

DSP chips faster than the TMS320C30 series used in the DREP electronics are now available. If the entire data acquisition system software has to be re-written anyway, it would make sense to upgrade the electronics at the same time. Diagnostics and tuning of the SQUIDs is cumbersome with the DREP electronics - the cover must be removed and probes attached to test points on the circuit board. Moving these test points to the outside of the electronics box would greatly simplify the diagnostic procedures.

The digital feedback loop uses a combination of a 12-bit digital-to-analog converter to generate the feedback signal and a reset counter to provide the very wide dynamic range. Ref 16 suggests that a 22-bit DAC is required to handle a dynamic range of $\pm 5000\ \Phi_o$ ($\sim \pm 5000$ nT/m with the gain on the new gradiometer). Modern DACs have 16 bits of resolution and some specialized boards have 20 bits. Therefore in the near future it might be possible to eliminate the reset portion of the digital feedback loop entirely.

5. Status of Other Mobile SQUID Programs

5.1 Germany (IPHT)

The German Defence Ministry has funded extensive work in airborne SQUID gradiometry since the late 1980's, originally performed by Dornier, and since 1997 by the Institut fur Physikalische Hochtechnologie (IPHT). Canada and Germany have cooperated on SQUID technology informally since the early 1990's and formally through Annex #8 to the Memorandum

of Understanding for the Exchange of Information in Advanced Magnetic Anomaly Detection Technologies since 1998.

The concept of operations for the German SQUID gradiometer is very similar to that which Canada envisaged - towed from a helicopter, battery powered with the electronics situated inside the tow-body, signals carried via fibre-optic cable to a PC-based data acquisition system mounted in the helicopter. In both cases the sensors are thin-film Niobium DC-SQUIDS, the noise specifications are similar, and the dewar is towed vertically.

The IPHT SQUID gradiometer, which is shown in Figure 6, differs from the Canadian SQUID gradiometer in the following ways:

1) the IPHT thin-film SQUID sensor and pickup coils are deposited on a single chip while the Canadian sensor used wire-wound pickup coils. This leads to inherently better balance in the German sensor (less common-mode problems),
2) the IPHT feedback loop is purely analog but the bandwidth is 1.5 MHz. This is adequate to remain locked even during rapid changes in the magnetic field,
3) because the feedback loop is analog, this implies that the signals one wishes to record are analog. IPHT uses a 24-bit A/D card to record the signals on a laptop-based data acquisition system,
4) the IPHT dewar is much smaller and lighter than the Canadian dewar so it can easily be moved by a single person, even when filled with liquid Helium.

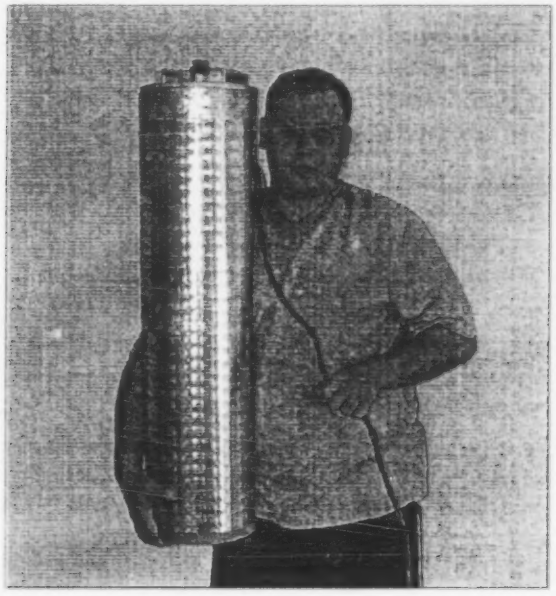

Figure 6. The IPHT dewar containing a 3-field component + 1 tensor gradient component SQUID sensor. Note the dewar is much smaller than the Canadian dewar.

The status of the German program as of August 2001 is as follows (Ref 25-26):

- a 3-field component + 1 gradient component gradiometer has been built and tested in the lab,
- the noise level on the stationary system has been measured at 10^{-5} $\Phi_o/\sqrt{Hz}$, the same as the design specification for the DREP gradiometer when in motion. Because the pickup coils and baselines are not the same as those on the DREP sensor, this flux noise translates to ~ 40 fT/m/√Hz, which is quite similar to what was measured during the quiet segments of the DREP flight data,
- the hysteresis caused by switching the direction of the ambient field from +50,000 nT to -50,000 nT was measured as 1.5×10^{-4} Φ_o,
- the system has been used to measure the magnetic signature of various helicopters at various heights above the sensor in order to estimate the tow-cable length required,
- the system is relatively immune to RF interference although some unlocking has been noted in field trials,
- the first Canadian tow-body was loaned to Germany to enable IPHT to conduct a flight trial with the 1-component gradiometer in the Fall of 2001. Further flight trials with a new tow-body, designed especially for the German dewar, are scheduled for 2002,
- a full 3-field component + 5 gradient tensor component system is scheduled for construction in the next phase of the project, after 2002.

5.2 Australia (CSIRO/BHP)

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and BHP Ltd have partnered to develop a thin-film RF-SQUID gradiometer made from YBCO for use in airborne time-domain electromagnetic (ATEM) surveying. In ATEM surveying, a transmitter on the aircraft generates a shaped magnetic-field pulse with a primary component at ~ 25-30 Hz. (See Figure 7) This pulse creates eddy currents in the conductive bodies in the ground and a receiver on the aircraft measures the decay rate of these secondary fields. Normally a coil is used as a receiver but SQUIDs offer the promise of measuring the decaying field to a later time before the signal is lost in the noise. This results in better conductivity resolution. The operational parameters of the BHP/CSIRO airborne high-T_C SQUID are given in Table 2. (Ref 27,28)

Table 2 Operational parameters of the BHP/CSIRO ATEM high-T_C SQUID system.

Parameter	Value
White Noise	350 fT/√Hz
1/f Knee	40 Hz
Slew Rate	100,000 Φ_o/second
Weight with Coolant	100,000 Φ_o/second
Power Requirements	12V @ 150 mA and -12 V @ 50 mA

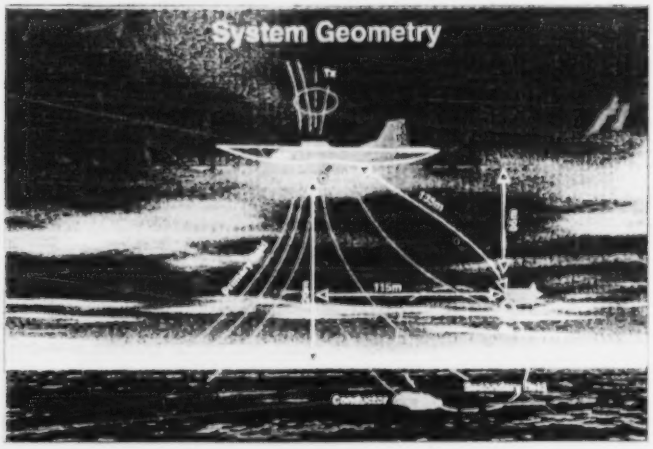

Figure 7. Operational concept for airborne time-domain electromagnetic surveying. The high-T_c SQUID sensor is used in the towed receiver.

CSIRO, with a consortium of Australian geophysical companies, is also in the early stages of developing an airborne high-T_c tensor gradiometer called GETMAG for deployment in 2003/2004 (Ref 29, 30). Significant improvements to the existing ATEM sensor are required to make it a useful geophysical tool and Table 3 gives the design specifications of the new sensor.

Table 3. Design parameters for the CSIRO GETMAG high-T_c SQUID system.

Parameter	Value
White Noise (1 KHz)	40 fT/√Hz
White Noise (1 Hz)	70 fT/√Hz
1/f Knee	1 Hz
Bandwidth	5 MHz
Slew Rate	10^5 Φ_o/second
Dynamic Range	190 dB

CSIRO hopes to improve the yield and reduce RF sensitivity of their SQUIDs, and develop a suspension system and software methods to reduce motion noise as part of the GETMAG project.

5.3 USA (CSS)

The Naval Surface Warfare Center, Coastal Systems Station (CSS) in Panama City Florida has been working on mobile SQUID gradiometers since the 1970's. However, since the mid-1980's they have focussed solely on underwater applications. A thorough review of their program can be found in Ref 31.

The original sensor for this research was based on bulk-and-wire Niobium technology and it was used to successfully develop signal processing algorithms. In 1995 it was deployed as part of a Mobile Underwater Debris Survey System (MUDSS) for detecting and localizing unexploded

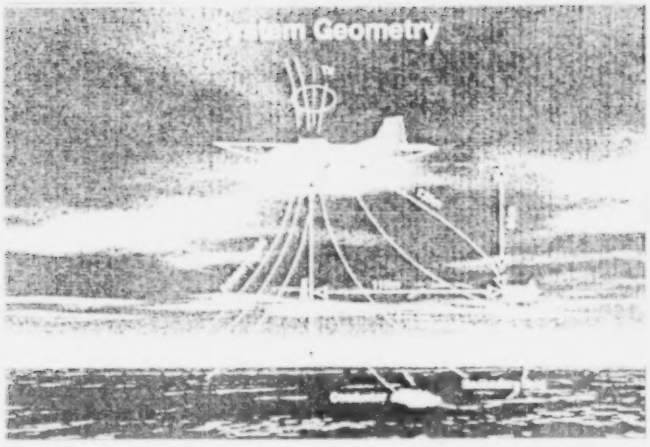

Figure 7: Operational concept for airborne time-domain electromagnetic surveying. The high T_c SQUID sensor is used in the towed receiver.

CSIRO, with a consortium of Australian geophysical companies, is now in the early stages of developing an airborne high-T_c sensor gradiometer called GETMAG for deployment in 2003-2004 (Ref 29, 30). Significant improvements to the existing ATEM sensor are required to make it a useful geophysical tool and Table 3 gives the design specifications of the new sensor.

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Parameter	Value
White Noise (1 KHz)	40 fT/√Hz
White Noise (1 Hz)	50 fT/√Hz
1/f Knee	1 Hz
Bandwidth	5 MHz
Slew Rate	10^6 Φ$_0$/second
Dynamic Range	190 dB

CSIRO hopes to improve the yield and reduce RF sensitivity of their SQUIDs, and develop a suspension system and software methods to reduce motion noise as part of the GETMAG project.

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The Naval Surface Warfare Center, Coastal Systems Station (CSS) in Panama City Florida has been working on mobile SQUID gradiometers since the 1970's. However, since the mid-1980's they have focussed solely on underwater applications. A thorough review of their program can be found in Ref 31.

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ordinance. The old sensor produced noise levels of ~ 3000 fT/m/√Hz at a frequency of 0.1 Hz during this trial.

In the mid-1990's the "Thin-film Gradiometer" program was begun to replace the older bulk-and-wire technology sensor with thin-film Niobium technology. This sensor had a demonstrated white noise level of 10^{-5} $\Phi_o/\sqrt{Hz}$ = 50 fT/m/√Hz with a "1/f" knee at 1 Hz in stationary tests (Ref 31). CSS had hoped to conduct the second phase of the MUDSS trials with the Thin-film Gradiometer but were unable to get the noise level in the moving system to an acceptable level. Unfortunately, CSS does not have funding to continue their work on the Thin-Film Gradiometer. (Ref 32)

CSS also developed a high-T_C gradiometer based on a 3-sensor approach to gradiometry (Ref 33). Although the device showed some promise in stationary tests, it was found to be very susceptible to RF interference. At the time of writing, CSS does not have funding to continue the work on high-T_C thin-film gradiometer either (Ref 32)

5.4 UK (QinetiQ)

In the United Kingdom, QinetiQ is investigating high-T_C gradiometers for applications in moving platforms. Early research showed that hysteresis would be a major problem in their YBCO SQUIDS (Ref 34), so a technique had to be developed to limit the dynamic range of the signals. QinetiQ has built a 3-axis Helmholtz-coil system to null the background field (Figure 8) and thereby reduce the dynamic range of the signals. The gradient signal is constructed by differencing individual magnetometer outputs, not measured with a single pickup coil as it is in the Canadian and German sensors. They have also seen RF interference problems with their SQUIDs and have constructed a special 25 mm-thick high-purity copper shield to fit outside the dewar but inside the Helmholtz-coils. This shield effectively applies a 4 Hz low-pass filter to the magnetic fields seen by the sensor. They believe that special shielding precautions will have to be implemented in a mobile configuration, although the existing copper shield will not be used because it significantly increases the Johnson noise of the system.

At present, the system consists of four sensors. Magnetometers 1,2,3 measure the components of the background field and drive the Helmholtz-coils. Magnetometers 1 and 4 are parallel and the outputs are subtracted to create a single gradient component. It has been used to (Ref 34-36):

1) measure the effect of background fields during cool-down,
2) measure the effect of re-orienting the sensor after cool-down,
3) characterize hysteresis,
4) determine the noise contributions from individual superconducting components, and
5) compare the actual noise performance to that predicted from simulations.

Table 4 contains the physical parameters and noise characteristics of their high-T_C system. QinetiQ is several years away from conducting mobile experiments with a full 5-tensor-component gradiometer.

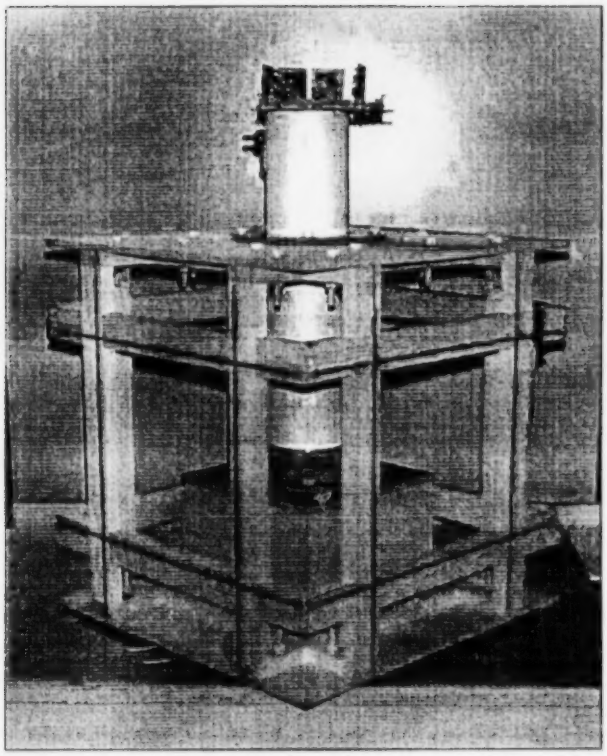

Figure 8. The QinetiQ high-T_C SQUID sensor and 3-axis Helmholtz-coil .

Table 4. Physical pareters and noise characterisits of the QinetiQ high-T_C SQUID sensor.

Parameter	Value
Baseline	10 cm
$\partial V/\partial \Phi_o$ at working point	98 $\mu V/\partial \Phi_o$
White Noise (zero-field cooled)	9×10^{-6} $\Phi_o/\sqrt{Hz}$
1/f knee (static bias)	100 Hz
Gain	3600 pT/Φ_o
Noise @ 1 Hz	~1 $pT/m/\sqrt{Hz}$

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Appendix A:

Full List of Reports Related to the Airborne SQUID Sensor Program

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RP-100-1272	Semi Annual SQUID Report	DIR E-208			Max Burbank
RP-102-0973	SQUID Report #2 (208)	DIR E-208			Randy Lomnes
RP-103-0274	Progress Report (208)	DIR E-208			
RP-107-0874	Progress Report (208)	DIR E-208			
RP-108-0275	Summary Report (DIR E-208)	DIR E-208			
RP-109-0375	Airborne Magnetometer	DSS OSP4-0119		Progress #1	
RP-111-0675	Final Summary Report (DIRE-208)	DIR E-208			
RP-112-0675	Progress Report (DIRE-208)	DIR E-208			
RP-116-0775	Airborne Magnetometer System	DSS OSP4-0119		Progress #2	
RP-117-0975	Airborne Magnetometer System	DSS OSP4-0119		Progress #3	
RP-118-0176	Airborne SQUID Magnetometer	DSS OSP4-0119		Progress #4	
RP-121-0476	Final Report - SQUID	DSS OSP4-0119			
RP-126-0677	Development and Flight Trial of Airborne SQUID	DSS OSR76-00041		Progress #2	
RP-128-0178	Airborne SQUID	DSS OSR76-00041		Progress #3	
RP-130-0678	SQUID	DSS OSR76-00041		Progress #4 Report	
RP-134-0479	Airborne SQUID	DSS OSR76-00041		Progress #5	
RP-135-0479	Horizontal Dewar Summary	ISS77-08160			
RP-150-0781	Final Report Investigation of Fixed Station Field Tests of a SQUID Gradiometer Array	DSS 08SB-3290020			
RP-159-1282	Final Report - Angular Motion Field Trials & Barge Trials of a SQUID Multi-Component Gradiometer/Magnetometer Array	DSS 8SB81-00290			CTF Systems Inc
RP-164-1083	Final Report - Experimental Tests of a SQUID Gradiometer Array from Moving Field Platforms	DSS 8SB81-00290			
RP-173-0685	Feasibility & Design Study of Low Power Miniaturized Electronics for Airborne Gradiometer Systems	DSS 08SB 97708-3-3810, serial 8SB83-00430	01-Jun-85	FINAL REPORT - Feasibility and Design Study of Miniaturized Electronics	Philip Kubik
RP-173-0685	New Figures* (Figures Only)	DSS 08SB 97708-3-3810, serial 8SB83-00430	01-Jun-85	New Figures for report.	Philip Kubik

RP-173-0685	Draft Copy - Low Power Miniaturized Electronics for Airborne Gradiometer System	DSS 08SB 97708-3-3810, serial 8SB83-00430	01-Jun-85	Feasibility and Design Study of the Miniaturized Electronics	Jiri Vrba and Jim McNeil
RP-180-0486	Development of Planar Superconducting Josephson Junction Microelectronic Devices	DSS 1SB85-00608	01-Apr-86	Progress Report #1	
RP-181-0786	Fabrication & Testing of Reduced Scale Superconducting Magnets	DSS 0SB84-00369	01-Jul-86	Final report submitted to TDC as per above DSS contract	Al Fife
RP-182-0986	Development of Planar Superconducting Josephson Junction Microelectronics Devices	DSS 1SB85-00608			
RP-183-1086 (a)	Development and Testing of SQUID Electronics Hybrid RF Amplifier	DSS 08SB 97708-4-5089/8SB84-00353	31-Oct-86	Final Report. Required final report submitted to supplement the release of the holdback claim	Jiri Vrba and Jim McNeil
RP-183-1286	Development of Planar Superconducting Josephson Junction Microelectronic Devices	DSS 1SB85-00608	15-Dec-86	Progress Review Report #3 For meeting with DREP	Jiri Vrba, Al Fife, Philip Kubik, Jack McCubbin
RP-185-0287	Development of Planar Superconducting Josephson Junctions Microelectronic Devices	DSS 08SB 97708-5-6787	12-Feb-87	Progress Report #4	Jiri Vrba, Al Fife, Jack McCubbin, Philip Kubik
RP-186-0487	Development of Planar Superconducting Josephson Junctions Microelectronic Devices	DSS 08SB 97708-5-6787	16-Apr-87	Progress Report #5 for review meeting with DREP	Jiri Vrba, Al Fife, Kevin Betts, Philip Kubik, Jack McCubbin
RP-189-0687	Development of Planar Superconducting Josephson Junction Microelectronic Devices	DSS 08SB 97708-5-6787	17-Jun-87	Progress Report #6 for last meeting with DREP re this contract	Jiri Vrba, Al Fife, Philip Kubik
RP-191-0887	Development of Planar Superconducting Josephson Junction Microelectronic Devices	DSS 08SB 97708-5-6787	01-Aug-87	Final Report of the contract	Al Fife, Philip Kubik, Jack McCubbin, Jiri Vrba
RP-192-1187	Investigation and Application of High Critical Temperature Superconducting Films	DSS 10SB.W7708-7-8580	10-Nov-87	Progress Report Meeting #1 with DREP Officials	Kevin Betts, Al Fife, Jack McCubbin, Jiri Vrba
RP-194-0188	Investigation & Application of High Critical Temperature Superconducting Films	DSS 10SB W7708-7-8580	26-Jan-88	Progress Report Meeting with DREP officials	Kevin Betts, Al Fife, Jack McCubbin, Jiri Vrba, Frank Wan
RP-196-0388	Investigation & Application of High Critical Temperature Superconducting Films	DSS 10SB W7708-7-8580	30-Mar-88	Progress Report Meeting #3 with DREP Officials	Kevin Betts, Al Fife, Jack McCubbin, Jiri Vrba, Frank Wan

RP-197-0688	Investigation and Application of High Critical Temperature Superconducting Films	DSS 10SB.W7708-7-8580	01-Jun-88	Progress Report No. 4	Kevin Betts, Al Fife, Jack McCubbin, Jiri Vrba
RP-200-0788	Investigation and Application of High Critical Temperature Superconducting Films	DSS 10SB W7708-7-8580	27-Jul-88	Progress Report No. 5	Kevin Betts, Al Fife, Sixtus Lee, Jack McCubbin, Jiri Vrba, Frank Wan
RP-201-1088 (a)	Investigation and Application of High Critical Temperature Superconducting Films	DSS 10SB W7708-7-8580	15-Oct-88	Progress Report No. 6	Kevin Betts, Al Fife, Philip Kubik, Sixtus Lee, Jack McCubbin, Jiri Vrba
RP-201-1088 (b)	Investigation and Application of High Critical Temperature Superconducting Films	DSS 10SB W7708-7-8580	15-Oct-88	Progress Report No. 6	Kevin Betts, Al Fife, Philip Kubik, Sixtus Lee, Jack McCubbin, Jiri Vrba
RP-202-0189(a), (b), (c), (d)	Investigation and Application of High Critical Temperature Superconducting Films	DSS 10SB W7708-7-8580	31-Jan-89	Final Report	Al Fife, Kevin Betts, Jiri Vrba
RP-203-0389(a), (b), (c), (d), (e), (f)	Final Report - Design, Consulting & Testing of Integrated Circuits for Magnetic Gradiometer Electronics	DSS 01SB 97708-5-6461	21-Mar-89	Disk (a) - text, (b) Fig. 1, (c) Fig. 2, (d) Fig. 3, (e) Fig. 4, (f) Fig. 5	Doug McKenzie, Jiri Vrba, Frank Wan
RP-206-0789	Investigation of Thallium-based Superconducting Devices	W7708-8-0437/01-SV	19-Jul-89	Progress Report #1	Jack McCubbin
RP-207-1089	Investigation of Thallium Based Superconducting Devices	W7708-8-0437/01-SV	18-Oct-89	Progress Report Number 2 Meeting with DREP and CRC	Jack McCubbin, Jennifer Enns, Al Fife, Normand Fortier, Jiri Vrba
RP-208-1289	Investigation of Thallium Based Superconducting Devices	W7708-8-0437/01-SV	18-Dec-89	Progress Report No. 3	Alan Cragg, Jennifer Enns, Al Fife, Normand Fortier, Jiri Vrba
RP-209-0390	Investigation of Thallium Based Superconducting Devices	W7708-8-0437/01-SV	19-Mar-90	Progress Report No. 4	Normand Fortier
RP-210-0890	Investigation of Thallium Based Superconducting Devices	W7708-8-0437/01-SV	02-Aug-90	Progress Report No. 5	Normand Fortier, Alan Cragg, Veryan Angus, Al Fife, Jiri Vrba
RP-211-0890	Development of High Sensitivity Thin Film DC SQUID and DC SQUID Electronics	DIR / DND File: 22070EP01		DIR Contract Initial Planning Meeting Report	Al Fife

RP-212-0890	To Build Working Thin Film RF SQUIDs	W7708-9-1406/01-XSA		Status Report	Al Fife
RP-214-1090	Investigation of Thallium Based Superconducting Devices	W7708-8-0437/01-SV		Progress Report #6	Normand Fortier, Alan Cragg, Al Fife, Jiri Vrba
RP-215-1090	DIR - "Development of High Sensitivity Thin Film DC SQUID and DC SQUID Electronics	DIR / DND File 22070EP01		Progress Report #2	Al Fife
RP-216-1090	To Build Working Thin Film RF SQUIDs	W7708-9-1406/01-XSA		Status Report #2	Al Fife
RP-217-1290	DIR - Development of High Sensitivity Thin Film DC SQUID and DC SQUID Electronics	DIR / DND File 22070EP01		Progress Report #3	Al Fife
RP-218-0391	DIR - Development of High Sensitivity Thin Film DC SQUID and DC SQUID Electronics	DIR / DND File 22070EP01		Progress Report #4	Al Fife
RP-219-0391	Final Report - Investigation of Thallium Based Superconducting Devices	W7708-8-0437/01-SV			Normand Fortier, Alan Cragg, Al Fife, Jiri Vrba
RP-221-0591	DIR - Development of High Sensitivity Thin Film DC SQUID and DC SQUID Electronics	DIR / DND File. 22070EP01		Progress Report #5	Al Fife
RP-222-0891	DIR - Development of High Sensitivity Thin Film DC SQUID and DC SQUID Electronics	DIR / DND File 22070EP01		Progress Report #6	Al Fife
RP-224-0192	Investigation and Development of Superconducting Infrared Detectors	W8477-9-CC11/01-SV	20-Jan-92	Progress Report #3	Normand Fortier, Veryan Angus, Alan Cragg, Jennifer Stevens, Al Fife, Jiri Vrba
RP-225-0392	Development of High Sensitivity Thin Film DC SQUIDs and DC SQUID Electronics	DIR / DND File. 22070EP01	20-Mar-92	Project Benefit Summary	Al Fife
RP-227-0592	Investigation and Design of a Superconducting Magnetic Gradiometer	W7708-0-0859/01-XSA		Final Report	Kevin Betts, Al Fife, Philip Kubik, Carlton Parfitt, Mark Tillotson, Guang Xu, Jiri Vrba
RP-228-0692	Development of High Sensitivity Thin Film DC SQUIDs and DC SQUID Electronics	DIR / DND File 22070EP01		DIR - Market and Commercialization Report	
RP-229-0892	Development of High Sensitivity Thin Film DC SQUID and DC SQUID Electronics	DIR / DND File 22070EP01	31-Jul-92	DIR Contract Final Report	Al Fife, Kevin Betts, Peter Spear, Murray Smith, Wim Westera, Jason Nomura, Ken Ferguson

RP-238-0394	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	28-Mar-94	Progress Report #1	A A. Fife, P R. Kubik
RP-242-0694	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	21-Jun-94	Progress Report #2	A.A Fife, P.R Kubik, M Tillotson
RP-244-0894	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	11-Aug-94	Progress Report Meeting #4	P R Kubik, A.A Fife, J. Vrba, K Ferguson, P Spear
RP-246-1194	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	24-Nov-94	Progress Report #3	A A Fife, P R Kubik, J Vrba, P Spear, M Smith, S. Marshall, K Ferguson
RP-251-0295	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	16-Feb-95	Progress Report #4	A A Fife, P R. Kubik, P. Spear, M Smith, M Tillotson
RP-253-0595	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	12-May-95	Progress Report #5	A.A. Fife, P R. Kubik, P. Spear, C Hunter, M Smith, M Tillotson
RP-254-1296	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	31-Dec-95	Progress Report #6	A.A. Fife, P R Kubik, P Spear, C Hunter, M. Smith, M Tillotson, K Betts, F. Habib, M Smith
RP-256-1096	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	17-Oct-96	Review Meeting #12	P R Kubik, R. Ockey, P. Spear
RP-258-0397	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	03-Mar-97	Review Meeting #13	P R. Kubik, R. Ockey, P Spear
RP-259-0697	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	26-Jun-97	Review Meeting #14	P R Kubik, R. Ockey, P. Spear, S Govorkov, L Satrijo
RP-260-1297	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	09-Dec-97	Review Meeting #15	P R Kubik, S. Govorkov
RP-261-0698	Design and Build a Low Noise SQUID Gradiometer	W7708-2-1306/01-XSA	12-06-98	System Tests	P.R. Kubik, S. Govorkov, J. Vrba, B Taylor

Appendix B:

List of Contracts Associated with the Airborne SQUID Sensor Program

Date	Contract #	Company	Title
1972	* DIR E-208	CTF	SQUID Magnetometery
1975	** DSS OSP4-0119	CTF	Airborne Magnetometer
1977	DSS OSR76-00041	CTF	Airborne SQUID
1980	DSS 08SB-3290020	CTF	SQUID Gradiometer Array
1982	DSS 8SB81-00290	CTF	Angular Motion Field Trials & Barge Trials of a SQUID Multi-Component Gradiometer/Magnetometer Array
1983	DSS 08SB 97708-3-3810, serial 8SB83-00430	CTF	Feasibility & Design Study of Low Power Miniaturized Electronics for Airborne Gradiometer Systems
1984	DSS 0SB84-00369	CTF	Fabrication & Testing of Reduced Scale Superconducting Magnets
1985	DSS 1SB85-00608	CTF	Development of Planar Superconducting Josephson Junction Microelectronic Devices
1984	DSS 08SB 97708-4-5089/8SB84-00353	CTF	Development and Testing of SQUID Electronics Hybrid RF Amplifier
1987	DSS 08SB 97708-5-6787	CTF	Development of Planar Superconducting Josephson Junctions Microelectronic Devices
1987	DSS 10SB.W7708-7-8580	CTF	Investigation and Application of High Critical Temperature Superconducting Films
1988	DSS 01SB 97708-5-6461	CTF	Design, Consulting & Testing of Integrated Circuits for Magnetic Gradiometer Electronics
1989	*** W7708-8-0437/01-SV	CTF	Investigation of Thallium-Based Superconducting Devices
1990	DIR / DND File 22070EP01	CTF	Development of High Sensitivity Thin Film DC SQUID and DC SQUID Electronics
1990	W7708-9-1406/01-XSA	CTF	Building Thin Film RF SQUIDs
1991	W7708-0-0859/01-XSA	CTF	Investigation and Design of a Superconducting Magnetic Gradiometer
1993	W7708-2-1306/01-XSA	CTF	Design and build a Low Noise SQUID Gradiometer
1998	W7708-7-0704/001/XSA	CTF	Superconducting Magnetic Gradiometer Flight Trial
1999	W7708-8-5972/A	CTF	Investigation and Repair of Airborne Superconducting Gradiometer System
1987	W7708-7-8303/01-SB	Signum	Development of a SQUID Controller and Communications Module
1988	W7708-7-9030/01-SB	Signum	Development of an A/D Module for the SQUID Sensor System
1989	W7708-0-0226/01-XSA	Bridgenorth	Enhancements of a Magnetic Gradiometer Data Acquisition and Processing System
90-92	**** W7708-1-0146	Bridgenorth	DREP Gradiometer Data Acquisition and Processing System (GDAPS)

* DIR refers to the Defence Industrial Research Program

** DSS refers to Department of Supply and Services

*** Numbers beginning with "W7708" are contracts from the Public Works and Government Services Canada

**** This is a "PWGSC Requisition Number", not a PWGSC "Contract Number"

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Building U-61, Uplands
Ottawa, Ontario, K1A 0R6
Attn: Mr. J. Bradley Nelson

1 – CTF Systems Inc.
15-1750 M^{c}Lean Ave.
Port Coquitlam, BC
V3C 1M9
Attn: Dr. H.S. Wilson

1 – Wehrtechnische Dienststelle fur Schiffe
und Marinewaffen
Berliner Strasse 115
24340 Eckernforde, Germany
Attn: Mr. M. Rothenbach

1 – NAVSEA Coastal Systems Station
Panama City
Sensing Technology Division
Panama City, Florida, 32407-7001
Attn: Dr. Ted Clem

1 – QinetiQ
St. Andrews Road, Malvern
Worcestershire, U.K. WR14 3PS
Attn: Dr. Mark Keene

1 – Department of Cryoelectronics
IPHT Jena
Winzerlaer Str. 10
D-07745 Jena / Germany
Attn: Dr. Meyer & Dr. Stolz

1 – Advanced Magnetics Group
CSIRO Exploration and Mining
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The superconducting quantum interference device (SQUID) program at the Defence Research Establishment Pacific began in the mid-1970's and continued until 1995. At that time the program was shifted to the Defence Research Establishment Atlantic where it continued until July 2000. The goal of this program was to develop and demonstrate a next-generation airborne magnetic gradient sensor for use in anti-submarine warfare. Almost all of the sensor development and a large portion of developing the data acquisition software was done under contract, but most of the research on characterizing noise sources in moving gradiometers, and designing/building the electronics and tow-body were done in-house. In June 1998, a flight test of the entire system was conducted using a Canadian Coast Guard helicopter. Although the results looked promising, the program was eventually terminated due to a lack of personnel and resources.

This report gives a brief history of the airborne SQUID program, the results achieved, and the unresolved issues at the time of termination. It also presents the status of other mobile SQUID sensor programs in the US, Germany, the UK, and Australia as of August 2001 for comparison.

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Superconducting Magnetometers

SQUID Gradiometers

Airborne SQUID systems